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How green desalination via SMRs is? A techno-environmental assessment of conceptual designs for MED-TVC and RO hybrid desalination

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ABSTRACT

Desalination raises concerns about the highly saline brine left after the process and usually disposed of in the sea and oceans. Further, desalination is an energy intensive process and since most of the operational units are powered using conventional fossil fuel, they are continually affecting the environment. The concerns of ecosystem degradation have always restricted the growth of the desalination industry. Due to the strong features of small modular reactors, the SMR-based desalination plants could offer significant improvements in the area of desalination environmental impacts. In this regard, this study investigates the techno-environmental aspects of three state-of-art conceptual MED-RO hybrid desalination systems coupled with a single NuScale SMR power unit to reduce the adverse discharge brine impacts. Hybridization of desalination systems could achieve the comparative advantages of both thermal distillation and membrane desalination aiming to address the socio-economic impacts originating from desalination. For this purpose, several new introduced parameters, including exergetic efficiency, Power-to-Water ratio, specific discharge salinity, intake-seawater-to-brine ratio, discharge stream enthalpy, and net greenhouse gas emissions precluded by using NuScale for different hybrid desalination schemes are assessed. The analysis was completed with the aid of the MATLAB software and THERMOFLEX module using an Excel interface. The main finding of this study is that marine impacts are better justified in hybrid desalination schemes and that further use clean reactor energy source would decrease the environmental burdens. The results show that in case of fully integrated hybrid system 244,000 tons of CO_2, 1012 tons of SO_2 and 910 tons of NO_x could be precluded annually from releasing into the atmosphere. However, hybrid systems generally have more significant marine effects which demonstrates the necessitated further studies and corrective actions.

1. Introduction

Freshwater is an essential requirement for nations' sustainable and socio-economic development. It is considered that facing water scarcity is one of the highlighted 21st-century global threats. Therefore, water resources would become the most valuable and strategic nations' resources. Desalinating seawater is a mature and energy-intensive process against other alternative approaches (i.e., Water conservation and management, pollution control) that started commercially in the 1930s. In some situations, it could be more costly. However, seawater desalination could be considered a reliable solution to conquer the huge gap between growing demand and available reserves for freshwater (Khater, 2003). In accord with the extensive investment in desalination markets, the global cumulative desalination capacities, with an annual average growth of 4.6 million m^3/day, raised to 114.9 million m^3/day through 20,971 projects around the world (Eke et al., 2020).

The most significant obstacles to the use of seawater desalination plants are related to the plants' bacterial sediments and organic compounds (Harvey et al., 2020; Jamieson et al., 2022) and the concerns associated with the environmental impacts. The first issue is being solved with the emergence of new antibacterial agents and water remediation methods (Ozdal and Gurkok, 2022; Zamani et al., 2021). The second issue, fossil fuels have been the prevailing source of energy for desalination plants over the past decades in both developed and economically developing nations., eventually leading to the release of large amounts of greenhouse gas emissions (GHG) and global warming (Nisan and Benzarti, 2008) and on the other hand, would not be compatible with sustainable development goals (Norouzi et al., 2020). Furthermore, The main characteristic of any desalination process is producing hypersaline discharge with unfavorable temperature and pH

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values, which causes devastating marine impacts.

Reactors with positive impacts on the environment and lower fluctuations in costs could provide a sustainable option to diversify the electricity production sources and offer a new energy source for seawater desalination. Furthermore, among various employment of reactor-based power plants for non-electrical products, Reactors with higher energy density than conventional fossil and renewable energy resources could be an attractive and practical solution for seawater desalination, particularly for countries facing water shortages and relying on domestic or foreign fossil fuel reserves (IAEA, 2015). The coined term "Reactor Desalination" (RD) defines producing potable water from seawater in a facility where a Nuclear Power Plant (NPP) is used as the dominant source to supply required energy in the form of heat or electricity for desalination. The facility may be committed individually to generating only electricity or utilizing a portion of total acquired power in the form of steam or electricity, providing a suitable substrate for producing potable water. RD has been a feasible option since the 1960s (IAEA, 2002).

Although the number of studies involved with the techno-economic aspects of RD in the literature is increasing, the potential environmental concerns of RD have not been got much attention (Al-Othman et al., 2019). Accordingly, this paper is aimed to investigate the nature and magnitude of environmental aspects of RD. It also aimed to materialize and evaluate the potential of designing higher complexity hybrid desalination systems with newcomers' small modular reactors (SMRs) power plants in reducing environmental concerns through a theoretical and computational model.

2. Environmental impacts of Reactor Desalination

Thermal distillation and membrane processes are the two leading developed seawater desalination technologies. Thermal distillation at a commercial scale, including multi-effect distillation (MED) and multi-stage flash distillation (MSF), started in the 1930s and has constantly been evolving since then; in the late 1950s, research and development on the reverse osmosis (RO) as the main application of membrane processes. Fossil fuel is the dominant source for desalination plants in operation. From a technical and economic standpoint, seawater desalination is an energy-intensive process, and growing desalination capacities based on fossil fuel sources would not be consistent with sustainable development over a long period. For instance, the required energy for de-salting one cubic meter of seawater diverges from 2.58 to 8.5 kWh/m^3 (Walsh et al., 2015).

Energy acquired in reactor power plants has the advantage of higher energy density than conventional fossil-fueled and renewable energy sources. With the continuously increased demand for fresh water coinciding with population growth and depletion of fossil fuels, developing countries currently need new energy sources. In these countries, new promising technologies of SMRs could address the economic risks and related safety issues of large-scale NPPs (Sovacool and Ramana, 2015).

For the last four decades, International Atomic Energy Agency (IAEA) has officially recognized RD as one of the promising solutions for co-generating electricity power and freshwater production (Gowin and Konishi, 1999). RD systems have several technical, safety, and environmental features that should be appropriately managed to obtain a sustainable strategy. These features need specific measures to minimize environmental damage due to many aspects, such as technology, operation, geographical, and meteorological conditions. As for RD plants, reliable ecological monitoring data is severely limited. However, the critical environmental concerns associated with RD could be addressed as coastal, marine, atmospheric, socio-economic, and public health and acceptance concerns (IAEA, 2010). Coastal impacts are related to the concerns relating to land requirements for construction and operation and characteristics such as noise and visual effects of the RD facility.

Any desalination process produces discharge brine with a higher-level dissolved solid than the feed stream. The high salinity and temperature of discharge brine caused by preheating and chemical pretreatment of the seawater can produce undesirable marine impacts. Besides, the brine disposal from RD facilities could also reduce the quality of the produced water or make the process more costly. However, adverse environmental effects of RD attributed to marine and coastal impacts due to seawater and brine discharge intake are considered lower than other cogeneration facilities, even in comparison with fossil-fueled desalination plants (Khan and Orfi, 2021). In addition, atmospheric effects, which originate from energy used for a specific desalination capacity, measure the magnitude of greenhouse gas emissions released into the atmosphere. Compared to fossil-fueled desalination plants or even renewable energies powered desalination, RDs can preclude emissions of GHG into the atmosphere to a large extent, even cleaner than renewable energies.

Moreover, socio-economics discusses the adverse impacts of the economic competitiveness of RD on capital development issues due to energy and water availability. Available data on the socio-economics of RD is quite limited, but the social and economic impacts of RD can be higher than other desalination plants, mainly due to cheap electricity and water production. Finally, Public health and public Receptance: quality, reliability of supply and radiation safety of the product water, concerns on plant safety, and public perception of these issues. The radiation safety of an RD plant, as well as other safety features, is highly satisfactory.

As discussed, seawater intake and high salinity of effluent discharge are two common RD concerns about coastal ecosystems (Al-Othman et al., 2019). However, several different measures could be considered to limit the associated concerns. These options should constrict the strength of the desalination waste discharge. However, among from two processes, hypersaline discharge produces more significant environmental impacts than intake seawater systems. For instance, the first issue could be addressed by employing indirect intake systems. However, more considerable attention is required to measure or treat the marine impacts of brine discharge. So the first step after providing the treatment of brine needed is to guarantee that the brine discharge point and seawater intake are far away from each other. This goal must be achieved because seawater quality will affect the desalination process.

3. Addressing brine management in Reactor Desalination

Advance brine management mechanisms could be categorized into two types: 1. reducing discharge brine concentration and 2. reducing discharge brine volume. The first approach includes any means to decrease salt from the effluent to reduce its environmental impacts. Hybridization, recovering energy from RO membranes, and diluting with the returned cooling water from the power plant's condenser are some actions that can be taken. The second approach is to increase the brine concentration in discharge flow to drop its volume (i.e., discharging brine to an evaporation pond; hybridization.)

Hybridization is a standard approach in both categories. Hybrid desalination systems include a reactor power system that employs a thermal distillation system with an RO system to accomplish the comparative advantages of these two desalination technologies.

In addition, RD requires sufficient seawater for the reactor and desalination plants, whether they use the joint intake seawater systems or not. Using the plant's condenser cooling water as the feed water of RO membranes increases the feed water temperature and enhances their permeability. RO plant recovery ratio usually increases by 1.5–3% per 1 °C (Sadeghi et al., 2020).

On the other hand, partially or feeding the RO membranes using the discharge of MED-TVC leads to having only a single hypersaline discharge stream which well fits in the second category. A bypass path could be utilized to control the volume flow rate of the feed water to the RO desalination unit or supply the required feed water if the thermal distillation plant is not operational.

Evaporation ponds are natural processes that could surpass the

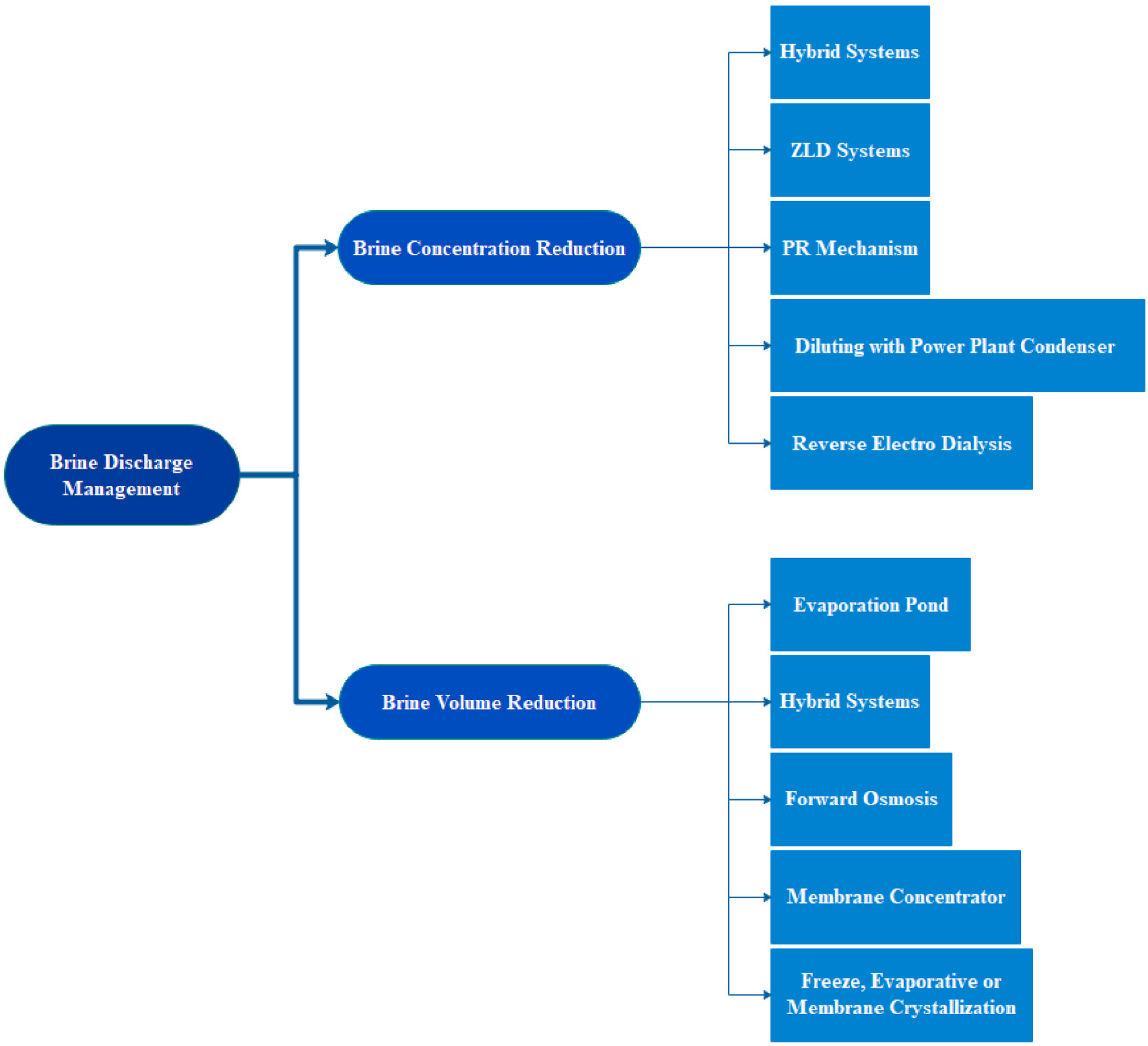


Fig. 1. Mechanisms for brine management in desalination systems.

evaporation of brine discharge. They are successfully used in the region with dry weather, high evaporation rates, and availability of land at a low cost. However, due to its high footprint, it does not apply to areas with high land costs. Accordingly, the application of evaporation ponds is limited to being implemented in small-scale inland desalination systems. Wind can also help reduce brine disposal's magnitude by evaporating the effluent brine. This system is called a wind-aided intensified evaporator (WAIE) (Gilron et al., 2019). Fig. 1 illustrates the various categories of brine management mechanisms based on the two measures discussed earlier in seawater desalination systems.

4. Role of small modular reactors in Reactor Desalination

SMR power plants, characterized by their smaller size, modular construction, and safety features, are designed chiefly to generate power more flexibly. However, they will still have technical challenges toward fully commercial. However, offering noteworthy innovations, including scalability to match the energy demands better, expandability to allow for future growth of demand, and reducing risks to facilitate co-location with the end-users energy consumers make SMRs a promising candidate for non-electrical energy applications such as seawater desalination (Locatelli et al., 2018).

Based on provided reports by IAEA, there is an increasing interest in the investment of SMRS in desalination (Al-Othman et al., 2019). Such designs as CAREM-25 in Argentina, IRIS in the USA, CNP-300 and ACP-100 in China, SMART in Korea, KLT-40 S in Russia, and PHWR-220 in India are currently in operation (Subki, 2021). However, the flexibility afforded by NuScale design, with a significantly enhanced level of plant safety and robustness, makes it uniquely suitable for desalination applications in various locations and coupling with multiple desalination technologies (D.T. Ingersoll et al., 2014). The main design

Table 1
Summarized design characteristics of NuScale SMR power plant (D.T. Ingersoll et al., 2014).

Parameters	Value
Ambient Temperature (°C)	27.0
Ambient pressure (bar)	1.014
Thermal power of each module (MW_{th})	160
Net electrical power of each module (MW_e)	50.0
Net electric efficiency (%)	>27
Steam pressure (bar)	35
Steam temperature (°C)	306
Steam flow (kg/s)	67.0
Feedwater temperature (°C)	149
Condenser pressure (bar)	0.085
Plant design life (years)	60
Fuel cycle length (months)	24
Average discharge burnup of fuel (MW.d/kgU)	50

Table 2
Surveyed literature considered environmental impacts and issues of RD.

Study	Year	Environmental impacts studied	Note
Schmidt and Gude (2021)	2021	Life-cycle GHG emissions intensity	The hypersaline desalination discharge considered would be diluted by the cooling discharge of the power-generating facility
Khan and Orfi (2021)	2021	Marine, coastal, atmospheric, sustainability, public health, public perception, and siting and co-location impacts	The environmental impacts of reactors-powered desalination were studied. Diluting the discharge brine with the plant cooling water is suggested.
Khamis and El-Emam (2020)	2020	Efficient water management in RD	Using IAEA's tool named WAMP
Al-Othman et al. (2019)	2019	Marine, coastal, and atmospheric impacts	An alternative approach is suggested, such as salt production and diluting with the plant cooling water to eliminate brine disposal.
Uthaman et al. (2018)	2018	Marine and coastal impacts	Studying the effect of using fly ash to enhance the durability of concrete and quality of intake seawater in RD activity
Laguntsov and Alexandrov (2018)	2018	Marine and coastal impacts	Designing an energy-efficient water supply system for the RD complex
(V. Anastasov and Khamis, 2010)	2010	Radiological health impact, Marine impacts, Atmospheric Impact	Presenting an overview of different environmental issues related to RD

parameters based on the NuScale Final Safety Analysis Report are presented in Table 1. The power generation system consists of twelve modules of NuScale SMR, two high-pressure turbines, and three low-pressure ones. Though to increase the efficiency of the turbines, two low-pressure and two intermediate-pressure feedwater reheaters have been applied to preheat the inlet flow to the reactor generator by steam flows have been extracted through turbines. A mechanical, induced-draft cooling tower provides cooling water to the main condensers and rejects heat to the environment. More technical and computational details are provided in section 8.

5. Scoping

There were 264 related research articles on RD in Scopus with the English language at the time of this paper (October 2022). The scientific literature reviewed consisted of peer-reviewed journals. The studies were reviewed based on the environmental aspects of RD plants, namely the present study's goal and scope. However, most of them are dedicated to the techno-economic analysis and only based on specific keywords, only a few studies have referred to the discussion of the environmental aspects of using reactors for desalination, and there is a lack of study on the environmental factors of using SMR power plants for desalination systems, especially desalination hybrid systems (see Table 2).

Anastasov and Khamis provided a comprehensive overview of environmental issues related to RD radiological health impact due to the possibility of migrating or forming tritiated water (T_2O) from steam generator into desalinated water in the distillation process (such as MED-TVC and MSF), marine impacts due to intake seawater and discharge of hypersaline desalination discharge, and atmospheric impact were the main points considered (Vladimir Anastasov and Khamis, 2010). Saleem, in 2010 performed an environmental impact assessment for the installed Karachi Reactor Desalination Power Plant (KANUPP) 1600 m^3/day of capacity (Saleem, 2010). Deployment of construction equipment and material, atmospheric impact, polluting groundwater due to drilling for feed water wells, hazard to public and aquatic life due to the possibility of rising the radiological activity of α, β, and tritium level, and impacts of discharged effluents were the main possible parameters affecting the environment. The study presented a checklist to carry out the assessment. In 2010 IAEA evaluated an RD's potential environmental issues to address the rising ecological awareness (IAEA, 2010). Othman and his colleagues allocated part of their comprehensive study to different aspects of RD (Al-Othman et al., 2019), including marine, coastal, and atmospheric issues. Khamis and El-Emam reviewed the latest IAEA tools named Water Management Programme (WAMP), developed to evaluate water management in Reactor power plants. The program enables users to perform comparisons of different cooling systems and reactor technologies under different site conditions.

Further, they discussed the feature of the IAEA tool in support of RD (Khamis and El-Emam, 2020). Recently, Khan and Orfi focused on the economic, environmental, and social issues associated with using Reactor energy in power generation and seawater desalination (Khan and Orfi, 2021). Moreover, this study the economic potential of hybrid Reactor and desalination technologies hybrid configurations.

The feasibility of implementing an RD plant in Turkey Point Reactor Generating Facility near Miami-Dade and Homestead of Florida is investigated by Schmit and Gude (Schmidt and Gude, 2021). The study discussed the atmospheric emissions saved through RD by comparing the life-cycle Greenhouse Gas Emissions (GHG) of conventional fossil fuel and renewable energy sources such as solar PV with Reactor energy sources. They concluded that reverse osmosis desalination plants powered by Reactor power produced water at the lowest cost among other options; it is still three times the cost of traditional water production. But considering the possibility of coupling desalination plants to reactor power plants despite the high costs is a legitimate solution to the environmental issue.

Besides the concerns about leakage of contaminated fluid into the desalination loop, hypersaline discharge is the primary environmental issue that must be addressed. Almost all surveyed studies suggested that diluting brine disposal of desalination plants with the cooling water of water plants would eliminate associated marine issues. The present study investigates the potential of possible hybrid RD layouts in decreasing brine disposal from reactor-powered desalination facilities.

6. Methods and procedures

This section explains the RD's working principle for integrating the NuScale reactor power plant with a hybrid RO-MED desalination system. Then, mathematical modeling of MED-TVC and RO desalination systems is presented.

6.1. Working principle of the NuScale hybrid RO-MED desalination plant

A general reactor-powered RO-MED hybrid desalination system is composed of three main sub-systems; (a) Reactor unit, which supplies heat and power, (b) RO-MED hybrid desalination system; and (c) intermediate loop.

In the first stage, the reactor produces electricity and supplies steam for the MED distillation process. The required steam is extracted through the secondary circuit and/or directly from the reactor's turbine. The quality and amount of extracted steam depend on what pressure and temperature are necessary for desalination. Furthermore, thermal and membrane desalination processes require electricity to run the pumps and the auxiliary systems and energize high-pressure pumps in reverse osmosis or the central compressor in a compressed vapor process.

NuScale, with a high degree of modularity design, could facilitate coupling the reactor-powered module's output to a desalination process in various ways. According to the literature, Ingersoll studied the cogeneration of electricity and water with coupling NuScale within three major desalination configurations from technical and economic points of view (D. T. Ingersoll et al., 2014). The first integration option considered was coupling a NuScale module to a MED-TVC distillation plant. In this configuration, the high-pressure steam is extracted directly from the exit of the steam generator. The second integration option was coupling an MSF distillation plant to a NuScale module by utilizing controlled extraction of medium-pressure steam from the turbine. It is worth reminding that MSF desalination technology can be easily used instead of the MED-TVC systems. The third and least integration option was coupling the NuScale plant to an RO desalination process. In this design, the electricity output from the standard turbine-generator system is supplied to the RO plant, and the normal power conversion systems of the NuScale plant are left unaltered.

Moreover, the utilization of low-pressure steam exhaust for thermal desalination was studied too. This integration scheme sends the extracted steam from a low backpressure type turbine operating with an exhaust pressure of 40 kPa to a reboiler. This configuration was assumed to be coupled to a MED cycle since this technology more readily accommodates low-pressure steam as the driving energy source.

To eliminate the possibility of contamination or any radioactive leakage into the potable water stream in distillation processes, such as MSF and MED, an intermediate loop consists of a heat exchanger, and a recirculation pump that connects the steam coming from the reactor steam circuit to the thermal desalination plant could be used.

In the MED-TVC process, Motive steam from the external source, in this paper, the extracted heat from the steam circuit of a NuScale power plant goes through the thermal vapor compressor (TVC) unit, which entrains and compresses a portion of the vapor generated in the last effect. Then the vapor flows toward falling pressure, while the seawater flows perpendicularly. The compressed steam is transferred to the tube side of the first effect's heat exchanger, while the seawater is sprayed on the tubes on the shell side (flashing box) feed. The brine spray absorbs the latent heat of the compressed vapor in the tubes, and its temperature increases to saturation. As a result, evaporation commences, and a smaller amount of this vapor forms the second stage onwards. The steam in tubes enters the second flashing box where a pressure drop leads a small amount of permeate to become vapor again and join the mainstream of vapor entering the next stage for condensation, not allowing the recovery amount of the unit to fall. This process is repeated for all effects.

On the other hand, reverse osmosis is a process where water with a high concentration of salts is pushed by pressure through a semipermeable membrane of reverse osmosis to obtain water with a low concentration of salts. A semipermeable membrane will permit some salts to pass but not others, depending on the size of the solids or molecules. The osmosis process is a process that occurs naturally, while reverse osmosis requires a supply of energy to the more concentrated solution.

6.2. *Mathematical modeling of NuScale hybrid desalination system*

NuScale module steam circuit, MED-TVC, and RO are the primary units in which thermodynamic analysis is applied to investigate the technical characteristics and environmental impacts of different integration coupling layouts.

6.2.1. *Modeling MED-TVC desalination system*

MED process is among the oldest technologies practiced in desalination. However, the presence of the MED was limited compared to the MSF in the past decades (Al-Shammiri and Safar, 1999). MED technology has experienced several improvements during the past ten years. These improvements include a significant increase in the capacity, a reduction in the tube scaling through proper design, and progress of the heat transfer with aluminum for surfaces (Fath et al., 2013). Further, to enhance the performance of the process, thermal Vapor Compressors are coupled with MED plants and formed as MED-TVC. Some studies predict that the MED processes may replace the MSF process soon because of the lower energy requirements (Fath et al., 2013; Mezher et al., 2011). Therefore, this technology was selected as the primary distillation mechanism in this paper.

Table 3
Inputs of the MED-TVC model (Jamshidian et al., 2022).

Parameter	Symbol	Value
Number of effects	n	7
The temperature of the first effect	$T_1(^{\circ}C)$	48
The temperature of the last effect	$T_n(^{\circ}C)$	68
The temperature of the seawater	$T_{cw}(^{\circ}C)$	33
The temperature of the feedwater	$T_f(^{\circ}C)$	45
Total Dissolved Solids of seawater	$X_f(ppm)$	45,000
Motive Steam temperature	$T_m(^{\circ}C)$	159
Motive Steam pressure	$P_m(kPa)$	45

The model inputs and practical equations of the MED-TVC model are presented in Table 3 and.

Table 4, respectively. The mathematical model is based on material and energy balances around evaporation effects, thermal vapor compressors, flash chambers, and end condensers introduced by (El-Dessouky and Ettouney, 2002).

The MED-TVC process was modeled using MATLAB software. Furthermore, A base schematic diagram of the MED-TVC distillation plant is provided in Fig. 2. Several simplifying assumptions were employed in this model as follows.

- Salt-free distillate ($X_d = 0$ ppm);
- Steady-state operation
- Existing an equal feed flow rate in each effect;
- Negligible thermodynamic losses
- The same boiling point elevation (BPE) for all effects equals 0.8 °C.

The main components of a MED-TVC system include the *n* number of evaporation boxes, namely effects, a flashing box, a condenser, and a thermal vapor compressor. As shown in Fig. 2, feed seawater (*F*) with the salinity of X_f leaves the condenser at T_f, where it exchanges heat with the vapors in the last effect. Then the stream is divided equally between the effects and is used to remove the excess heat entering the system by the hot motive steam. Compressed steam from the thermal vapor compressor is supplied into the tube side of the first effect and warms up the sprayed feed seawater to the boiling temperature of the first effect (T1), also known as top brine temperature. Then, a portion of the feed evaporates and generates a certain amount of vapor (D_1), which is directed to the second effect as the heat source at the lower temperature and pressure than the previous effect, while so on it goes to the last effect at a lower pressure than the preceding effect. Part of the condensate from the first effect returns to its source while the remnant enters the first flashing box. The purpose of the flashing boxes is to recover the heat from the condensed fresh water. The remaining part of the brine leaves the first effect (B_1). The temperature of vapor initiated in the first effect (Tv_1) is lower than the boiling temperature (T_1) by a small value known as the boiling point elevation (BPE).

6.2.2. *Modeling RO desalination system*

The reverse osmosis (RO) process is based on osmotic pressure, salt rejection, and recovery ratio. An RO desalination plant consists mainly of a high-pressure pump and a membrane module, as shown in the schematic representation of Fig. 2. Table 5 summarizes the simple and practical model of the RO process (IAEA, 2013). Subscripts *f, d,* and *p* refer to feedwater, rejected brine, and permeate stream, respectively. Almost all modern large-scale RO plants use power recovery turbines (RET), where the pressure of the rejected brine stream is utilized to reduce the overall power consumption of the system. Inputs of the model developed for the RO unit are also shown in Table 6.

One of the critical design parameters of RO systems that play a

Table 4
Mathematical modeling of the forward MED-TVC unit (El-Dessouky and Ettouney, 2002).

Equations	Definition
$M_f = \frac{X_b}{(X_b - X_f)} M_b = M_f - Wdr_{TH}$ (1)	n: the number of effects
$D_1 = \frac{M_d}{\left(1 + \sum_{i=1}^{n} \lambda_{v1}/\lambda_{vi}\right)} \quad D_i = D_1 \cdot \frac{\lambda_{v1}}{\lambda_{vi}}$ (2)	M_f: the intake seawater flow
$\lambda = 2589.583 + 0.9156 \cdot T - 4.834 \times 10^{-2} \cdot T^2$	M_b: the rejected brine flow from the latest effect
$\Delta T_t = T_s - T_n \quad \Delta T_1 = \frac{\Delta T_t}{U_1 \sum_{i=1}^{n} 1/U_i} \quad \Delta T_i = \Delta T_1 \cdot \frac{U_1}{U_i}$ (3)	D_i: the flowrate profile of distillate in each effect
$U_1 = 1.9695 + 1.2057e - 2 \cdot T_b - 8.5989e - 5 \cdot {T_b}^2 + 2.5651e - 7 \cdot {T_b}^3$	λ_{vi}: the latent heat values of seawater
$U_{i+1} = 0.95 \cdot U_i$	T_s: the inlet vapor temperature
$T_1 = T_s - \Delta T_1 \quad T_i = T_{i-1} - \Delta T_i$ (4)	ΔT_i: the temperature drop of brine in each effect
$T_{v_i} = T_i - BPE$ (5)	ΔT_t: the temperature drop across all effects
$B_1 = M_f - D_1 \quad B_{i+1} = B_i - D_{i+1}$ (6)	T_i: the temperature profile of brine in each effect
$X_1 = X_f \cdot \frac{M_f}{B_1} \quad X_i = X_{i-1} \cdot \frac{B_{i-1}}{B_i}$ (7)	X_f: the salinity of seawater
$A_1 = \frac{(D_m + D_{ev}) \cdot \lambda_s}{U_1 \cdot (T_s - T_1)} \quad A_{i+1} = \frac{D_i \cdot \lambda_i}{U_i \cdot (\Delta T_{loss})}$ (7)	X_b: the saltiness of rejected disposal
$Ra = 0.296 \cdot \frac{{P_s}^{1.19}}{{P_{ev}}^{1.04}} \cdot \left(\frac{P_m}{P_s}\right)^{0.015} \cdot \frac{PCF}{TCF}$ (8)	X_i: the salinity of brine in each effect
$P_s = 1000 \cdot \exp\left(\frac{-3892.7}{T_s + 273.15 - 42.6776} + 9.5\right)$	U_i: the overall heat transfer coefficient in each effect
$P_{ev} = 1000 \cdot \exp\left(\frac{-3892.7}{T_{v_n} + 273.15 - 42.6776} + 9.5\right)$	A_i: the heat transfer area of each effect
$PCF = 3e - 7 \cdot {P_m}^2 - 0.9e - 3 \cdot P_m + 1.6101$	Ra: the entrainment ratio
$TCF = 2e - 8 \cdot (T_n - \Delta T_{loss})^2 - 0.6e - 3 \cdot (T_n - \Delta T_{loss}) + 1.0047$	M_m: the motive steam flow rate
$M_s = \left(D_1 \lambda_{v1} + \frac{M_f C_p \cdot (T_1 - T_f)}{\lambda_{T_s}} \quad M_m = \frac{M_s}{1 + 1/Ra} \quad (9)\right)$	M_s: the compressed vapor flow rate
$Q_c = (D_n - M_{ev}) \times \lambda_{vn} \quad A_c = \frac{Q_c}{U_c \cdot (LMTD)_c}$ (10)	M_{ev}: the entrain vapor flow rate
$LMTD_c = \frac{T_f - T_{cw}}{\ln \frac{T_n - T_{cw}}{T_n - T_f}}$ (11)	Q_c: the condenser thermal load
$U_C = 1.7194 + 3.2063e - 2 \cdot T_{v_n} - 1.5971e - 5 \cdot {T_{v_n}}^2 + 1.9918e - 7 \cdot {T_{v_n}}^3$	ΔT_{loss}: the thermodynamic temperature losses
$Q_{MED-TVC} = M_m \cdot \lambda_{T_m}$	$Q_{MED-TVC}$: the total thermal load of the MED-TVC unit

crucial role in the environmental performance of this paper's proposed RD conceptual designs is the intake feedwater temperature (T_{im}). Modabber and Khoshgoftar Manesh discussed that increasing the feed water temperature causes a rise in the viscosity, and consequently, the water penetration rate through the membrane in the RO units increases (Vazini Modabber and Khoshgoftar Manesh, 2020). This phenomenon leads to the net driving pressure (P_{NDP}) needed decreases. On the other hand, rising T_{im} increases the osmotic pressure ($P_{Osmotic}$) which deteriorates permeability through the membrane. The high head pressure rise (ΔH) needed is the summation of P_{NDP} , $P_{Osmotic}$ and pressure drops. Fig. 3 shows the trade-off between these two contradicting effects and the high head pressure of pumps. As can be seen, ΔH decreases smoothly with increasing the feedwater temperature.

7. Possible NuScale hybrid desalination systems

Table 7 summarizes the key parameters for integrating eight NuScale modules with desalination options for a total capacity of 190,000 m^3/day. The noteworthy point is that it was reported that one NuScale module is capable of yielding enough steam to produce up to 88,000 m^3/day of fresh water. However, the study only considered simple integration schematics. But there are many ways to improve desalination plants' flexibility, efficiency, environmental impacts, and product cost. For example, to increase the efficiency of the RO process, the feedwater stream to the RO units can be preheated by the hot water returning from the plant's condenser. This design has the most flexibility in balancing electrical and water outputs but requires a relatively clean feedwater stream or significant amounts of water pre-treatment. In another configuration, the discharge of thermal distillation plants can be used as the feed water of the RO process to reduce the rejected brine in response to concerns about marine impacts. Furthermore, the products of RO and thermal desalination units could be mixed to adjust the salinity of the final product.

As described above, hybridization could be one promising technique to improve the environmental performance of RD. Hybrid RD plants consist of a reactor that employs a mixture of thermal distillation technologies and a membrane desalination process to optimize potable water production from seawater. They could work in a stand-alone way or an integrated way and finally mix the fresh water produced to adjust the salinity of the final product. Here, in this paper, in the conceptual design investigations of hybrid RD plants, the aspect that restricts joint utilization of desalination facilities is the environmental impact.

A demonstration-scale, classical stand-alone hybrid RD in which the distillate from an RO desalination component is mixed with an MSF has already been undertaken by India. In addition to India, China and Russia also considered coupling the hybrid (MED-RO) plants. Table 8 provides

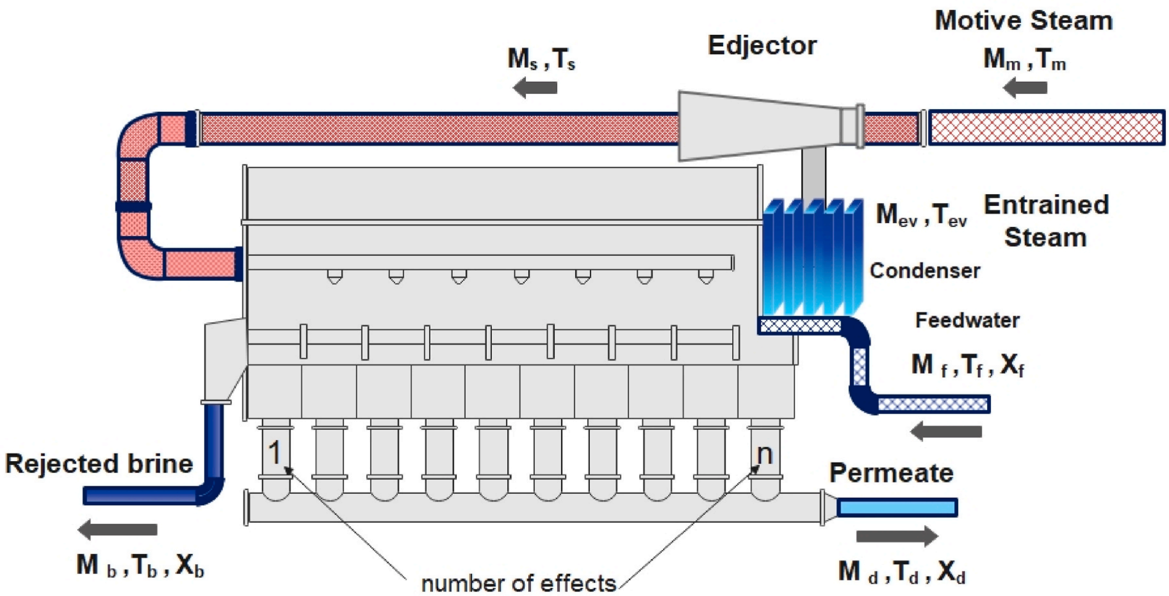


Fig. 2. Basic schematic of a MED-TVC unit.

a summary characteristics of these configurations.

[1,2]The environmental impact on marine organisms of a Reactor power plant co-located with desalination plants depends strongly on the cooling system used by the power plant. The original design of the NuScale power plant would use a dry cooling tower system, which ultimately prevents any marine environmental impacts. Therefore, regarding the zero-marine impact of the NuScale power plant, co-located desalination units are responsible for the marine impacts.

The proposed conceptual layouts of NuScale hybrid desalination systems are described in this section. The main feature of these plans is the focus on reducing the environmental impacts of RD, including 1-zero liquid discharged brine to decrease the marine impacts and 2-increasing the total desalination performance to contribute as much as possible in preventing the emission of greenhouse gases in comparison fossil power plants.

The hybrid desalination model simulates integrating a NuScale module through an Intermediate Circuit (IC) with MED-TVC, MSF, and RO desalination systems. The thermodynamic analysis is applied to investigate different coupling configurations' thermal characteristics and performance.

The main difference in the thermal coupling scheme of Reactor and fossil plants to the thermal distillation process is the necessary installation of an intermediate heat exchanger circuit (IC) to ensure that even in a hypothetical and highly improbable double rupture in the steam generator and the IC tube no contamination can migrate into the desalination system and the potable produced water. The IC could operate at a higher or lower pressure than the second loop of the Reactor power plant and the first stage of the thermal distillation installations. For MED-TVC systems, the IC contains a reboiler to produce the clean steam needed for the first effect of the desalination plant, and in the case of MSF systems, hot water from the heat exchanger can be used directly in the brine heater of the plant. However, these desalination technologies generate a large amount of hyper-saline wastewater (discharge), harming the aquatic environment, water cycle, and human health (Adlard, 2020).

The WAIV is the most straightforward crystallization technique. WAIV units utilize wind energy to evaporate liquid brine on several vertically hung hydrophilic sheets that enhance the surface area for evaporation. As the liquid flows down and spreads slowly on the hydrophilic sheets, it contacts the wind blowing past the sheets and evaporates (Gilron et al., 2019). This technique is an innovative alternative to traditional evaporation ponds.

7.1. Configuration A, simple hybrid desalination System-I

The principle of the present simple hybrid desalination system as a classical hybridization layout is to couple a NuScale module to a RO desalination unit with a co-located thermal distillation installation in a stand-alone way in which the operating conditions of each one do not affect the operating conditions of the other facility. Fig. 5 illustrates the simple hybrid desalination system consisting of a thermal distillation unit MED-TVC and an RO desalination plant.

Ingersoll suggested two distinct coupling mechanisms for integrating NuScale with the thermal desalination options (D. T. Ingersoll et al., 2014). The first integration option considered is utilizing the main high-pressure steam from the exit of the steam generator to drive the MED-TVC unit through an IC reboiler. The second option is using controlled extraction of medium-pressure steam from the turbine to supply heat to IC and provide heat in the form of hot water or steam. Part of the electricity output from the turbine-generator system is provided to the RO plant to run the necessary high-pressure pumps and to the thermal distillation plant to supply auxiliary equipment.

This hybrid configuration allows increased flexibility in water product quality. Usually, the desalinated water produced from a thermal distillation technology with a TDS level lower than ten ppm is of distilled quality which is suitable only for industrial use; meanwhile, the TDS level for RO technology is in the range of 300–500 ppm, which is ideal for drinking conforming to World Health Organization (WHO) standards. Therefore, blending thermal distillation technology-produced water with RO water minimizes the requirement for additive injection to the thermal distillation process and, as a result, lowers water production costs. Finally, the discharge brine would lead to a WAIV unit.

7.2. Configuration B, simple hybrid desalination System-II

As shown in Fig. 6, this configuration differs from Configuration A in that the feedwater stream to the RO unit is preheated by the hot water returning from the condenser (No. 15). This concept utilizes low-grade

[1] Low-Temperature MED (LT-MED).
[2] High-Temperature MED (HTME).

Table 5
Mathematical modeling of the RO unit.

Equations	Definition
$Rr = 1 - \frac{0.0115}{P_{MAX}} \cdot X_f$ (1) $M_f = \frac{Wdr_{RO}}{Rr} \quad M_b = \left(\frac{1}{Rr} - 1\right) \cdot Wdr_{RO}$ (2) $X_d = 0.00125 \cdot X_f \cdot J_w \cdot \left(1 + \frac{1}{1 - Rr}\right) \cdot (1 + 0.03 \cdot (\mathrm{T}_{im} - 25))$ (3 − 1) $X_b = \frac{X_f}{1 - Rr}$ (3 − 2) $M_b \cdot X_b = M_f \cdot X_f - M_d \cdot X_d$ (4) $P_{NDP} = \frac{1}{J_w} \cdot \frac{28.2}{k_f} \cdot \frac{\exp\left(3500 \cdot \left(\frac{1}{273 + \mathrm{T}_{im}} - \frac{1}{298}\right)\right)}{1.5 - 0.75\mathrm{e} - 5 \cdot \left(1 + \frac{1}{1 - Rr}\right) \cdot X_f}$ (5) $\pi(bar) = 0.0000348 \times (T + 273.15) \times X/14.7$ $P_{Osmotic} = \frac{\pi_{in} + \pi_{out}}{2}$ (6) $P_{HP} = P_{NDP} + P_{Osmotic}$ (7) $Q_{\Delta \mathrm{H}}(MW) = \frac{M_f \cdot \frac{1000}{24 \times 3600} \times Q_{\Delta \mathrm{H}}}{98600}$ (8) $RET\ (MW) = (1 - Rr) \times Q_{\Delta \mathrm{H}}$ (8) $Q_{total}(MW) = Q_{\Delta \mathrm{H}} - RET$ (9)	Rr: recovery ratio Wdr_{RO}: RO plant capacity (m^3/day) M: stream flow rate (m^3/day) X: stream salinity (ppm) J_w: the ratio of nominal permeate flux to design permeate flux T_{im}: feedwater intake temperature (°C) P_{NDP}: net driving pressure of membrane process (bar) $P_{Osmotic}$: Average osmotic pressure (bar) π_{in}: the approximated inlet osmotic pressure (bar) π_{out}: the approximated outlet osmotic pressure (bar) P_{HP}: High head pump pressure rise (bar) k_f: the fouling factor $Q_{\Delta \mathrm{H}}$: high-pressure pump power (MW) Q_{total}: the total power use (MW)

Table 6
Inputs of the RO model.

Parameter	Symbol	Value
Feedwater salinity	X_f	45,000
Feedwater temperature	T_m	33
Feedwater mass flow	M_f	144.3
Recovery factor	Rr	42%
the ratio of nominal permeate flux to design permeate flux	J_w	2.044
Fouling factor	k_f	0.8

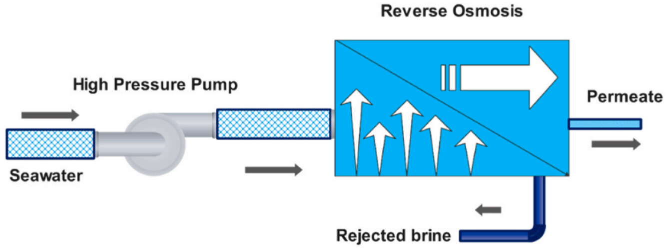


Fig. 3. Basic schematic of RO unit.

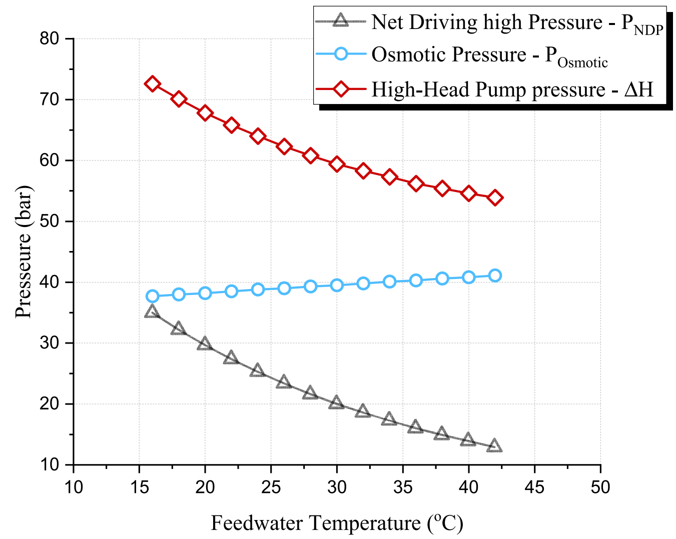


Fig. 4. The effect of seawater temperature on the high-head pressure pump.

Table 7
Summary of technical and economic analysis of integration NuScale with different desalination plants provided by Ingersoll and Houghton (D. T. Ingersoll et al., 2014).

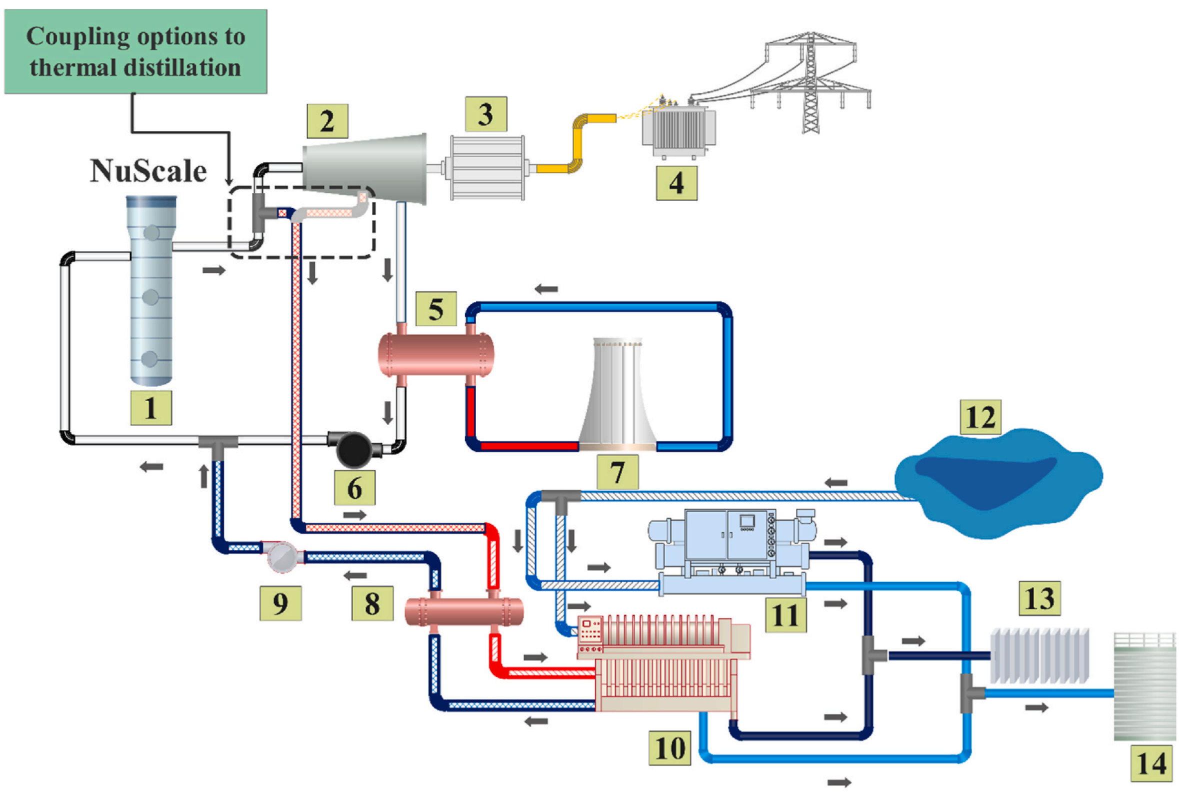
Desalination Configuration	MED-TVC (High-Pressure)	MSF (Medium-Pressure)	MED (Medium-Pressure)	MED (Low-pressure)	RO
Coupled Plants Parameters					
Net plant electrical output (MWe)	296	227	293	334	348
Exhaust steam-driven plant characteristics					
Steam Pressure (MPa)	3.5	0.2	0.2	0.04	N/A
Steam temperature (°C)	300	130	130	N/A	N/A
Steam flow available (kg/s)	67	39.3	22.4	48	N/A
GOR (kg water/kg steam)	12–17	8	14	12	N/A
Top Brine Temperature (°C)	70	90	70	70	N/A
Number of Units coupled	N/A	7	7	4	N/A
Economic Parameters					
Capital Cost of NuScale (M$)	1800	1800	1800	1800	1800
Capital Cost of Desalination Plant (M$)	N/A	15.1	13.3	13.3	14.2

heat that is otherwise discharged into the ambient for preheating treatment of the feedwater of RO units. There is an essential saving in pumping energy if a preheating treatment to the feed seawater is done; Fig. 4 shows the pressure needed to apply to the feedwater temperature. In this case, it has also been mentioned that one alternative could be to use the cooling water of the condenser.

The operation of RO installations at higher temperatures increases the efficiency of the process. However, as the feed stream's temperature rises, the TDS of the distilled water goes up. But this effect is manageable (IAEA, 2007).

Table 8
Principal characteristics of existing hybrid RD projects.

Country	Project Name	Desalination System	Reactor Name	Thermal Power (MW.)	Capacity (m^3/day)	Hybridization degree
India	MAPS	MSF-RO	PHWT-220	220.0	6300.0	71%
China	CRP	LT-MED + RO	NHR-200	200.0	Variable	N/A
Russia	IPPE	HT-MED + RO	KLT-40C	40.0	218,000.0	44%
		HT-MED + RO	NIKA-70	70.0	144,000.0	50%

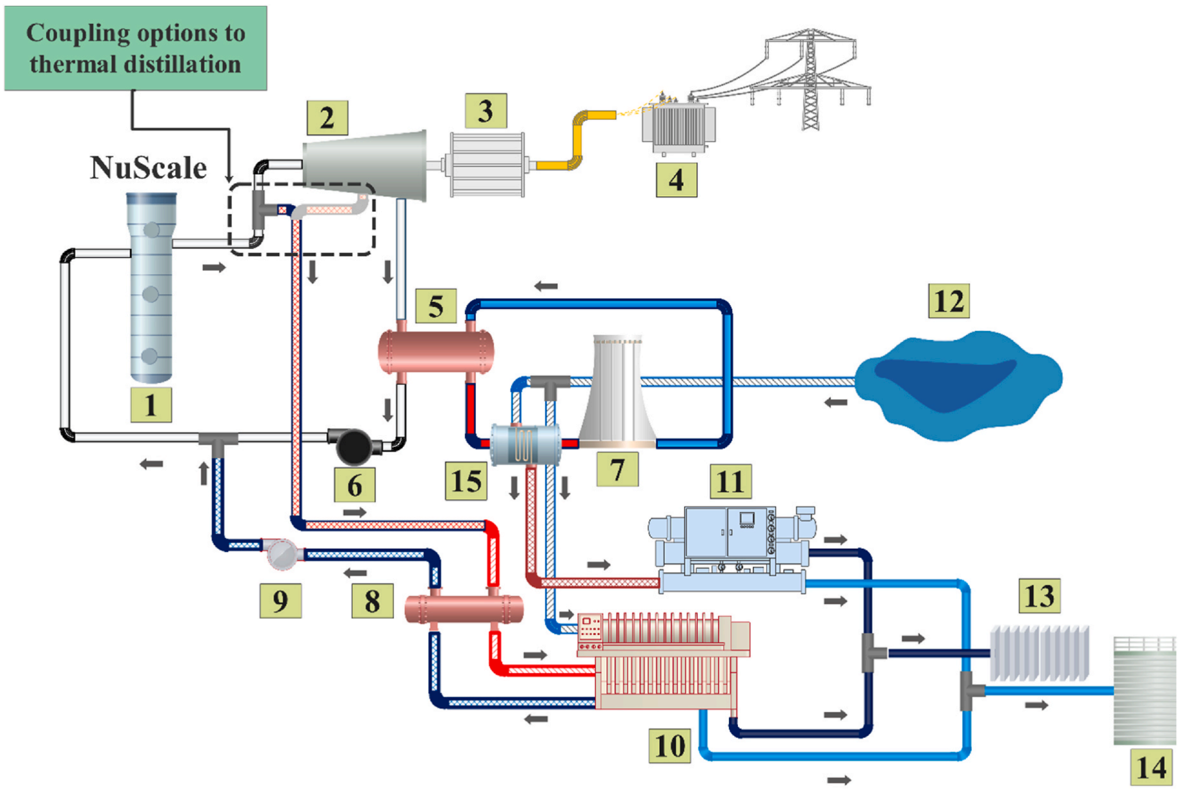


#	Description
1	NuScale 160 MW_{th} module
2	Steam turbine
3	Generator
4	Transformer
5	Condenser
6	Main cooling pump
7	Cooling tower
8	IC heat exchanger/reboiler
9	Pump
10	Thermal distillation unit (MED-TVC or MSF)
11	RO unit
12	Intake seawater
13	WAIV unit
14	Permeate Storage

Fig. 5. Schematic of Configuration A, Simple Hybrid Desalination system-I.

7.3. Configuration C, integrated hybrid desalination system

This integrated hybrid system differs from simple hybrid systems in that the thermal and membrane plants are designed as fully integrated. In this layout, the rejected brine of the MED-TVC or MSF system is transferred to RO installation as feedwater. On the other hand, seawater intake directly affects the pre and after-treatment process and significantly impacts the evaluation of the produced water cost. Hence, the water intake costs for the RO installations should be removed, and only after-treatment costs should be considered in the detailed evaluation.



#	Description
1	NuScale 160 MW_{th} module
2	Steam turbine
3	Generator
4	Transformer
5	Condenser
6	Main cooling pump
7	Cooling tower
8	IC heat exchanger/reboiler
9	Pump
10	Thermal distillation unit (MED-TVC or MSF)
11	RO unit
12	Intake seawater
13	Brine discharge
14	WAIV unit
15	RO unit feedwater preheater condenser

Fig. 6. Schematic of Configuration B, Simple Hybrid Desalination system-II with preheating RO installation feed.

Therefore, this configuration could increase the efficiency of the RO units, and the volume flow rate of discharge brine can be optimized, which reduces the marine impacts of the Reactor cogeneration plant. Fig. 7 illustrates the layout of the proposed hybrid desalination system and components.

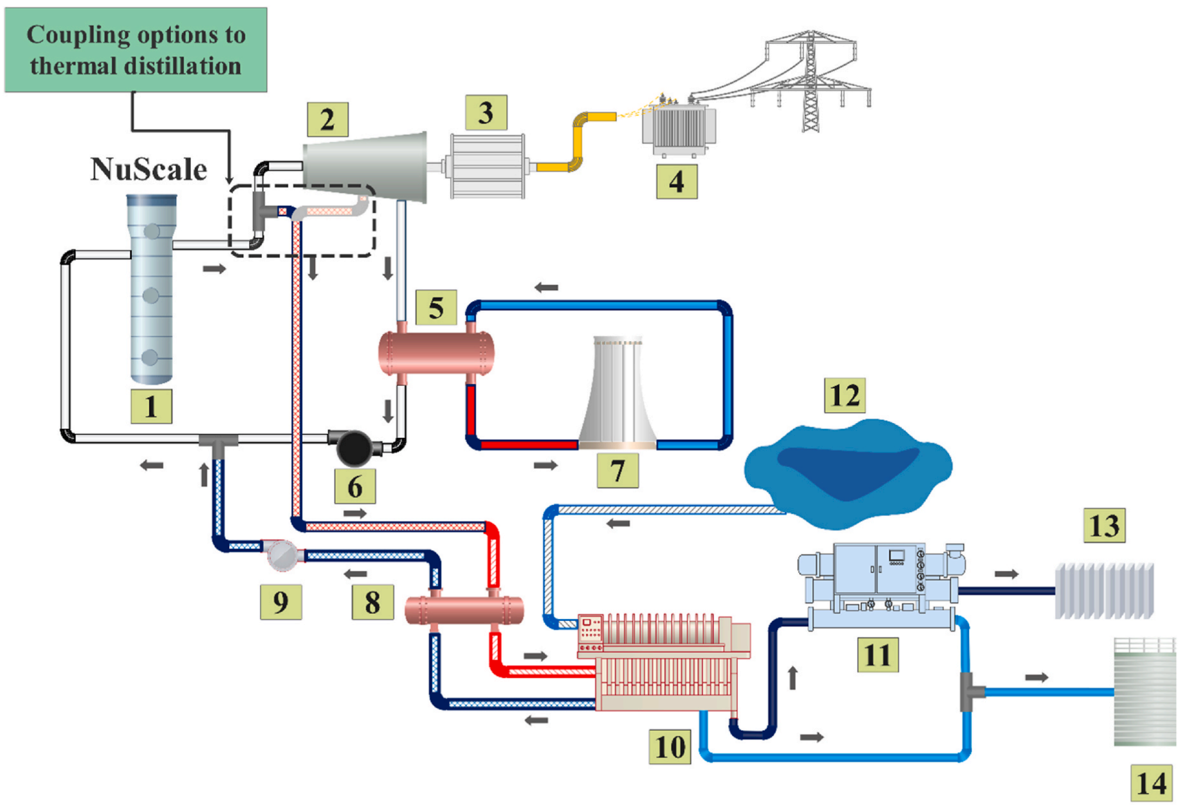
Applying reverse osmosis leads to an increase in water TDS over time. In hybrid plants, due to the high-purity water produced by the thermal method (MED), membranes are replaced after more extended periods, resulting in lower operating costs.

Compared to the single MED method, hybrid water desalination has a tremendous environmental advantage: the water and salt concentration produced by MED have a relatively high temperature that requires cooling to protect the environment. Because RO water has a much lower temperature, combining MED and RO water can significantly contribute to lowering the temperature of the end product.

Furthermore, the brine produced via RO has a high level of concentration. Returning it to the sea in large volumes poses a significant risk to ocean life and marine ecosystems, but combining the low-concentration brine produced through MED with RO brine will help moderate the water pumped out into the sea.

7.4. Techno-environment analysis of different systems

The authors perform a techno-environmental assessment to examine and compare the performance of the three proposed ZLD hybrid systems. The evaluation would be based on five parameters, including (i)



#	Description
1	NuScale 160 MW_{th} module
2	Steam turbine
3	Generator
4	Transformer
5	Condenser
6	Main cooling pump
7	Cooling tower
8	IC heat exchanger/reboiler
9	Pump
10	Thermal distillation unit (MED-TVC or MSF)
11	RO unit
12	Intake seawater
13	WAIV unit
14	Permeate Storage

Fig. 7. Schematic of Configuration A, Integrated hybrid desalination system-I.

exergetic efficiency, (ii) Power-to-Water (P/W) ratio, (iii) specific discharge salinity, (iv) seawater-to-brine ratio, (v) discharge enthalpy, (vi) net greenhouse gas (GHG) emissions off-set.

The main consequence of extracting steam is lost electricity production. The level of lost electricity is equal to the electricity that could be produced if the heat extracted for the distillation plant was provided at the lowest available temperature and strongly depends on its extracted conditions. Two main constraints could limit the feasible steam extraction points: 1- the amount and quality of required thermal energy in the form of steam to be extracted for desalination application and 2- technical constraints from the power plant side, such as maximum extraction flows in turbine bleed points, minimum reduction in power plant efficiency, or specific lay-out in the turbine hall. To ensure that the quality of bleed steam is qualified for considered and proposed coupling layouts, a thermodynamic analysis should be performed to find the optimum configuration with the lowest power loss.

Exergetic efficiency (γ) for the RD process with thermal systems can be described as the ratio of the maximum shaft work (W_{Shaft}) that could be acquired by a thermotical cycle between the condensing temperature of the desalination plant (T_{cm}) and the lower available cooling temper-

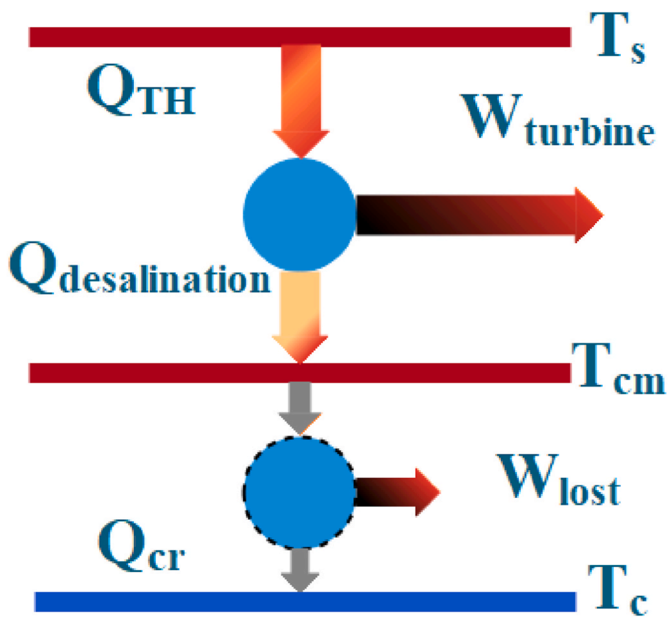


Fig. 8. Illustration of the lost work concept caused by the extraction of heat in a dual-purpose plant.

Table 9
The comparison of the performance of the two extracting options.

	Option-I	Option-II
Desalination Technology	MED-TVC	MED-TVC
Total Electricity Output (Mwe)	27.9	28.0
Total Distillation Water Plant Power (MW)	57.2	57.2
Exergy Lost (MW)	18.2	18.3
Exergetic Efficiency (γ)	0.456	0.450

ature (T_c) to the exergy lost or the exergy supplied to the desalination system (ΔEx_{Lost}) as:

$$\gamma = \frac{Max\ W_{Shaft}}{\Delta Ex_{Lost}} \tag{1}$$

where, the maximum shaft work or $Max\ W_{Shaft}$ is defined based on the Carnot Cycle efficiency (η) as follows:

$$Max\ W_{Shaft}(kW) = \eta \times \left(Q^{Th}_{Desalination} - Q_{cr}\right)$$
$$\eta = 1 - \frac{Tc}{Tcm} \tag{2}$$

In Eq. (2) Q_{cr} is the reject heat load and could be calculated as follows:

$$Q_{cr}(kW) = Q^{Th}_{Desalination} \times (1-\eta) \tag{3}$$

Moreover, the exergy lost or ΔEx_{Lost} could be defined based on the second law of thermodynamics as the following:

$$\Delta Ex_{Lost}\ (kW) = \dot{m}[(h_{Tcm} - h_{Tc}) - T_0(S_{Tcm} - S_{Tc})] \tag{4}$$

where, $\dot{m}$ is the mass flow rate of extracted steam, and h and S are enthalpy and entropy, respectively.

The workflow diagram of a sample dual-purpose power plant is illustrated in Fig. 8. The main steam temperature is in °C. The thermal utilization factor (UF) is another index that could show the performance of the cogeneration system and is defined as the energy utilized by the end-user to produce energy primarily.

$$UF = \frac{W_{turbine} + Q^{Desalination}_{Th}}{Q_{Th}} \tag{5}$$

Further, the impact of two options in extracting steam on the performance parameters is shown in Table 9. It can be seen that despite a little more electricity output of Option-II, Option-I has more exergetic efficiency, which offers more useful exergy is lost in Option-II.

The P/W is a design characteristic that could indicate the specific energy consumed in different hybrid desalination layouts and is defined as the amount of power consumed per total capacity of freshwater produced a day (Caldera et al., 2017).

$$P\Big/W\left(\frac{kWh}{m^3/day}\right) = \frac{Energy\ \ consumed(kWh)}{Freshwater\ capacity\left(m^3/day\right)} \tag{6}$$

The P/W parameter is similarly affected by several factors. This will be particularly important in cases where the P/W has to be minimized in favor of water production. In this study, to achieve a more favorable result, the consumed energy in hybrid systems is considered as the summation of thermal energy in the distillation process and electrical power in the RO system, which is transformed into thermal energy by the obtained cogeneration efficiency. Next, specific brine discharge salinity is defined as the ratio of the discharge salinity to the stream's flow:

$$\xi\left(\frac{ppm}{\frac{kg}{s}}\right) = \frac{X_b}{\dot{m}_b} \tag{7}$$

This parameter provides an estimation of discharge salinity impact. Lower values guarantee a lower concentration of dissolved solids but a higher discharge volume and vice versa. Another related parameter is the seawater-to-brine ratio as follows:

$$\chi = \frac{\dot{m}_b}{\dot{m}_f} \tag{8}$$

Seawater-to-brine is an environmental parameter that indicates the recovery of freshwater from seawater. This parameter represents proper discharge brine management competence in integrated hybrid layout desalination systems.

Another parameter that could be used to assess the environmental impacts of desalination on seawater/marine is the total energy/heat in the form of discharge brine with higher enthalpy reject to sea. This parameter could be defined as the difference in enthalpy of intake seawater (h_{T_f}) and discharge brine (h_{T_b}) following:

$$h(kW) = m_b^{MED-TVC} \times \left(h_{T_b}^{MED-TVC} - h_{T_f}^{MED-TVC}\right) + m_b^{RO} \times \left(h_{T_b}^{RO} - h_{T_f}^{RO}\right) \tag{9}$$

where, $m_b^{MED-TVC}$ and m_b^{RO} are the mass flow rate of MED-TVC and RO systems, respectively. Moreover, the developed library for seawater's thermodynamic properties in MATLAB software was used To calculate environmental characteristics (Sadri et al., 2017).

Regardless of the emissions emitted through the several stages of fuel fabrication in the life cycle, Reactor energy is considered a cleaner energy source when compared with conventional (Oil – 547–935 tons CO_2e/GWh and natural gas – 362–891 tons CO_2e/GWh) and even other renewable energy sources such as solar-PV (13–731 tons CO_2e/GWh) in terms of life cycle greenhouse gas (GHG) emission intensity (Schmidt and Gude, 2021).

The role of RD in reducing the annual amount of air pollution that could be precluded from releasing into the atmosphere is defined as the GHG off-set which is estimated based on the delivered energy to desalination plants as steam, and the emissions factor of GHGs (i.e., ν_{CO_2} = 620 gr/kWhe, ν_{SO_2} = 2.57 gr/kWhe, and ν_{NOx} = 2.31 gr/kWhe for instance in Iran (Nazari et al., 2010) as follows:

Table 10
Validation of the MED-TVC mathematical model.

Outputs	Present Study	Ref. (Jamshidian et al., 2022)	Error
Discharge Brine Salinity (X_b)	65,000	64,839	0.25%
Discharge brine mass flow (M_d)	27.14	27.51	1.3%
Motive steam mass flow (M_m)	2.35	2.57	8.5%
Specific thermal load (kW/kg/s)	150	141	6.8%

Table 11
Validation of the RO mathematical model using DEEP5 software.

Outputs	Present Study	DEEP5	Error
Discharge brine mass flow (M_b)	86.2	90.0	4.2%
Discharge brine salinity (X_b)	75,000	77,586	3.3%
Permeate salinity (X_d)	388	400	3.0%
High head pump pressure (P_{HP})	71.5	72.0	0.7%
Specific electrical load (kWh/m^3)	6.19	6.25	0.9%

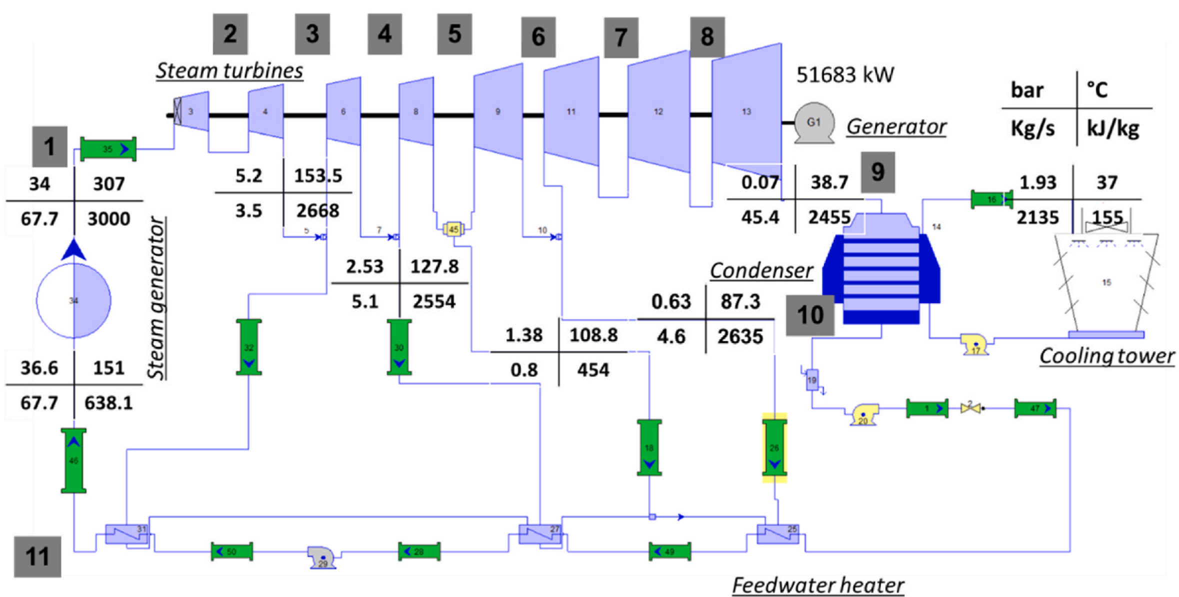
$$\begin{aligned} \Delta CO_2\left(\frac{ton}{yr}\right) &= wdrc \times Q \times 8760 \times AF \times \nu_{CO_2} \\ \Delta SO_2\left(\frac{ton}{yr}\right) &= wdrc \times Q \times 8760 \times AF \times \nu_{SO_2} \\ \Delta NOx\left(\frac{ton}{yr}\right) &= wdrc \times Q \times 8760 \times AF \times \nu_{NOx} \end{aligned} \tag{10}$$

where ΔCO_2, ΔSO_2 and ΔNOx are net GHG off-sets, Q is the specific energy consumption in cogeneration plant in $\left(\frac{kwh}{m^3/day}\right)$, and AF is the annual (annum) cogeneration plant on-stream time factor.

8. Results and discussion

In this section, the different technical and environmental aspects of all introduced coupling configurations are analyzed. For modeling of the RO and MED-TVC systems, MATLAB software is employed to determine the operational requirements of each hybrid desalination layout discussed in section 6.

The accuracy of the MED-TVC model is investigated against Jamshidian and his colleagues' recent study (Jamshidian et al., 2022) for a unit with a capacity of 2000 m^3/day in the Qeshm Multi-effect distillation site in the southern part of Iran. The inputs from this study have been implemented and the results were compared, as shown in Table 10.



	Pressure		Temperature		Mass flow	
	Simulation value	Ref value	Simulation value	Ref value	Simulation value	Ref value
Stream 1	36.6	35.1	151.0	148.0	67.7	67.0
Stream 2	34.0	33.9	307.0	306.0	67.7	67.0
Stream 3	5.2	4.9	153.5	151.6	3.5	3.3
Stream 4	2.5	2.42	127.8	126.5	5.1	5.0
Stream 5	1.38	1.38	108.8	108.3	0.8	1.0
Stream 6	0.63	0.58	87.3	85.1	4.6	4.0
Stream 7	0.08	0.08	38.7	41.6	45.4	51.9
Stream 8	1.93	1.92	37.0	37.7	2135	2312

Fig. 9. The comparison between simulation result and reference values for base NuScale power plant.

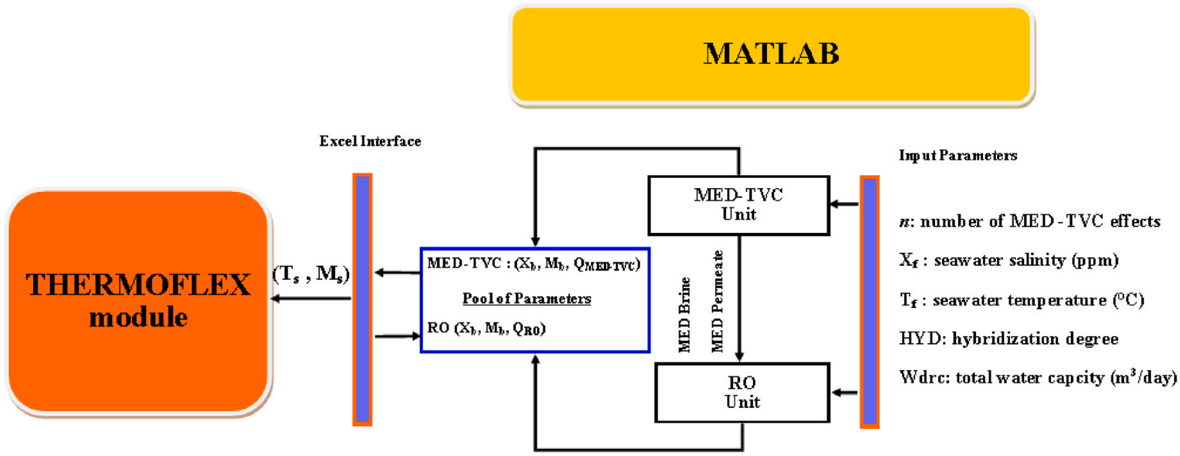


Fig. 10. Schematic of the implemented solution diagram.

Table 12
The main thermodynamic characteristics of different hybrid desalination configurations in coupling with the steam cycle of the NuScale power plant.

	$Q^{Th}_{MED-TVC}(kW)$	$Q^{aux}_{MED-TVC}(kW)$	$Q^{El}_{RO}(kW)$	T_{cm} (°C)	Max $W_{Shaft}(kW)$	ΔEx_{Lost} (kW)
Configuration A-I[a]	36521.2	366.4	535.5	283.7	7067.4	34891.1
Configuration A-II	36508.9	365.0	535.3	304.3	7626.2	34438.3
Configuration B–I	36521.1	366.3	535.5	283.7	7067.4	34891.1
Configuration B-II	36525.5	366.3	535.5	304.3	7724.9	34904.9
Configuration C–I	36521.2	366.4	901.7	283.7	7067.4	34891.1
Configuration C-II	36508.9	366.3	752.2	304.3	7724.5	34876.3

[a] as it was noted, two integration options are considered, I) utilizing main high-pressure steam from the exit of the steam generator and II) utilizing controlled extraction of medium-pressure steam from the turbine.

As can be seen in this table, the error value is less than 8.5%.

Moreover, the developed model for the RO desalination plant was also validated using DEEP5 software (IAEA, 2013; Kavvadias and Khamis, 2010), and the results are presented in Table 11.

Moreover, to determine the heat and mass balances of the NuScale power plant in the case of extracting steam to supply the required thermal energy for operating the MED-TVC desalination system through an IC and returning to a condensate state, THERMOFLEX energy system modeling software is employed. In Fig. 9, the results of NuScale steam cycle thermodynamic analysis, including steam flow rate, pressure, temperature, and enthalpy with the data, are available in the safety analysis report of the NuScale, which provided by the vendor has been compared (NuScale Power, 2012). The calculations are performed based on the rated thermal power of 160 MW. Much analysis is required to determine the best coupling configuration of energy source and desalination systems. Naserbegi and Aghaie performed an exergy analysis to find the optimum extracting steam condition of a dual source reactor and solar power plant to utilize for a MED-TVC desalination plant (Naserbegi and Aghaie, 2021).

Further, Norouzi et al. studied the thermodynamic efficiency of a modular reactor power plant using the second thermodynamic law (Norouzi et al., 2021). However, in the present study, the main focus is placed on the environmental aspects of RD. A coupling algorithm is developed and used in MATLAB software to employ the operational requirements for each hybrid design for different hybridization levels in the THERMOFLEX module and calculate the new state of the steam cycle. One of the main capabilities of THERMOFLEX is the ability to be linked with Excel. Therefore, exporting outputs from THERMOFLEX to MATLAB software or being initialized through MATLAB software is possible. The suggested algorithm is illustrated in Fig. 10. In this algorithm, only the temperature and mass flow of the motive steam (T_s and m_s) in the MED-TVC distillation process are transferred to THERMOFLEX. Further, the inputs of this algorithm are some of the technical and design parameters of the hybrid desalination system, including total capacity, hybridization degree, salinity, and seawater temperature. Here, the hybridization degree is defined as the ratio of the considered capacity for the distillation process to the total capacity. The hybridization degree is defined as the ratio of the supposed capacity for thermal distillation to the total capacity ($\frac{Wdr_{Th}}{Wdr_{total}}$)

Table 12 provides the main thermodynamic characteristics for different coupling configurations, including the thermal and auxiliary load required for MED-TVC and RO process and the desalination plant's condensing temperature (T_{cm}). It was explained that two possible extraction points are investigated in this study. *Option-I)* utilizing main high-pressure steam from the exit of the steam generator and *Option II)* utilizing controlled extraction of medium-pressure steam from the turbine. The total desalination capacity in the base case is 8000 m^3/day with a hybridization degree of 50%. In all scenarios, the main steam temperature (T_s) is considered 307 °C, and the lower available cooling temperature (T_c) or the temperature of returning point is considered 38.7 °C.

As can be seen, the total power requirement for the MED-TVC system in all conceptual configurations is almost a constant value. Therefore, it is reasonable to expect that the exergy is lost or ΔEx_{Lost} remains the same. The calculations show that practically 3500 kW of total power plant exergy is lost due to desalination. It was discussed in section 6.2 that the salinity of feed water in RO systems affects the required osmosis pressure and, consequently, the required electrical power for driving the high-pressure pumps. Therefore it is reasonable to see that the electrical energy consumed by the RO system in the integrated hybrid configuration (Configuration C) in which the rejected brine of the MED-TVC desalination system used as feed water is at least 40% higher the configurations A and B which the salinity of feed water is same as the seawater desalination.

Moreover, based on the definitions provided in section 7.4 for performance parameters, including exergetic efficiency (γ), the thermal utilization factor or *UF*, and P/W parameter it was observed that they

Table 13
The main environmental characteristics of different hybrid desalination configurations in coupling with the steam cycle of the NuScale power plant.

	$X_f^{MED-TVC}$ (ppm)	$m_f^{MED-TVC}$ (kg/s)	X_f^{RO} (ppm)	m_f^{RO} (kg/s)	$X_b^{MED-TVC}$ (ppm)	$m_b^{MED-TVC}$ (kg/s)	X_b^{RO} (ppm)	m_B^{RO} (kg/s)	$h_b^{MED-TVC}$ (kW)	h_b^{RO} (kJ/kg)	Discharge salinity to sea (ppm)	Discharge flow to sea (kg/s)	Intake seawater flow (kg/s)
Configuration A-I	45,000	409.7	45,000	144.3	67,500	69.25	75,000	86.6	1.67E5	1.38E5	71,000	155.8	554.0
Configuration A-II	45,000	409.7	45,000	144.3	67,500	115.4	75,000	89.45	1.67E5	1.38E5	71,000	201.9	554.0
Configuration B-I	45,000	409.7	45,000	90.7	67,500	69.25	75,000	90.68	1.67E5	1.54E5	72,000	155.8	500.4
Configuration B-II	45,000	409.7	45,000	90.7	67,500	115.4	75,000	90.68	1.67E5	1.54E5	72,000	201.9	500.4
Configuration C-I	45,000	682.8	67,500	115.4	67,500	115.4	112,500	43.28	–	1.67E5	112,500	158.7	798.2
Configuration C-II	45,000	682.8	67,500	115.4	67,500	115.4	112,500	43.28	–	1.67E5	112,500	158.7	798.2

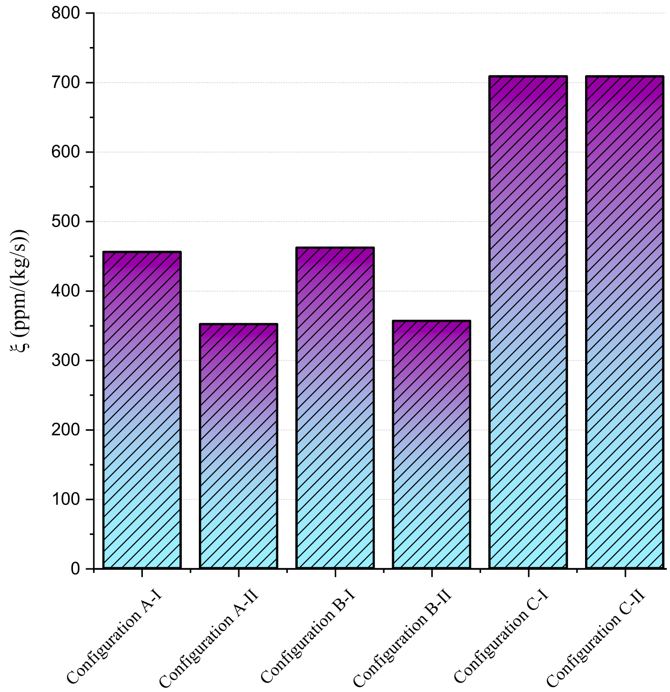


Fig. 11. The comparison of salinity impact in final discharged brine flow to the sea.

are equal to constant values. In detail, for all configurations, the γ is equivalent to a constant value of about 0.2. and the thermal utilization factor or *UF* which is only dependent on the integration lay-out; when the required steam is extracted from the exit of the steam generator, the UF would be 81%, and through Option II, UF would be 78%. Therefore, utilizing the main high-pressure steam from the exit of the steam generator leads to higher cogeneration performance. But it should be noted that the steam has to be withdrawn from a point where its saturation temperature is above the max brine temperature for MED-TVC desalination, considering an additional temperature drop due to the IC heat exchangers. Finally, the P/W ratio is almost equal to 5.5.

From the above discussions, it can be concluded that we are facing an RD system but in different coupling configurations with the same functionality from a technical point of view. The authors suggest that environmental concerns are better justified in cogeneration schemes.

In continue, the environmental performance of different hybrid system configurations is investigated. Table 13 provides the parameters

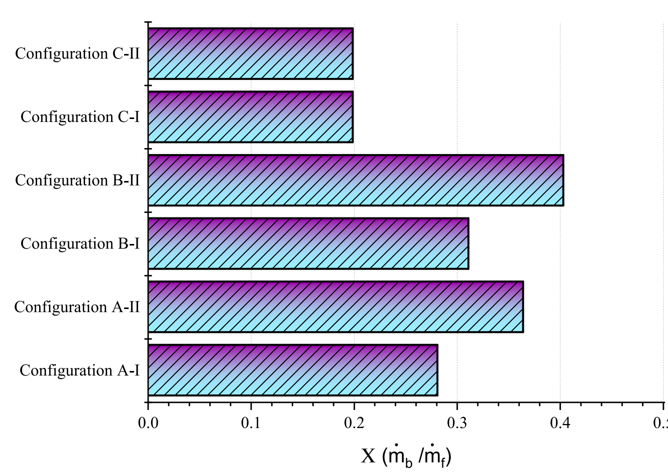


Fig. 12. The comparison of seawater-to-brine stream in different coupling layouts.

Table 14
The comparison of GHG off-set factor in different lay-outs.

	ΔCO_2 (Mton/yr)	ΔSO_2 (ton/yr)	ΔNO_x (ton/yr)
Configuration A-I	0.242	1003.1	901.6
Configuration A-II	0.238	988.7	888.6
Configuration B–I	0.242	1003.1	901.6
Configuration B-II	0.241	1000.9	899.6
Configuration C–I	0.237	985.4	885.7
Configuration C-II	0.244	1012.7	910.2

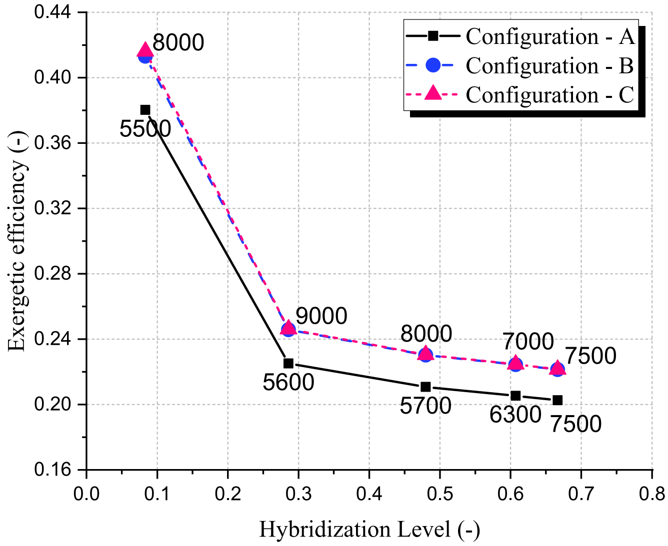


Fig. 13. The exergetic efficiency changes in terms of hybridization degree for different schematics.

related to the ecological impacts of varying coupling configurations. It was observed that the integration coupling concept (configuration C) has the discharge with the highest salinity (112,500 ppm) and seawater inlet flow (798.2 kg/s). Moreover, based on the results, the calculation of heat rejected to sea due to discharge brine show that configuration C has the lowest impact on the sea temperature while simple layouts (configurations A and B) have a more considerable influence due to higher discharge stream flow. Fig. 11 compares the marine impact of hybrid desalination systems. As defined, ξ is the ratio of discharge salinity to the discharge brine flow rate to the sea. It can be seen from the discharge salinity and discharge flow columns of Table 13 that the discharge brine stream of integrated configurations (Configuration C–I and C-II) involves more dissolved solids, while the simple layouts carry almost an equal dissolved solid. Therefore, while the discharge flow rate in arrangements C is practically low, it is rational that values are higher, and this configuration has a more severe effect on the environment. Fig. 12 shows the recovery characteristic (χ) of different configurations by providing the ratio of discharge brine flow rate to seawater intake. Table 9 shows that the discharge flow rate of the first option of both configurations, A and B, is the same and lower than coupling option 2. In contrast, the intake seawater flow for each configuration is the same. Among all arrangements, Configuration B, with the second integration option more incredible, has the highest capability to recover freshwater.

Finally, the potential of RD to preclude releasing greenhouse gas emissions, including CO_2, SO_2, and NO_x, compared to fossil-fueled desalination plants has been shown in Table 14. As seen, in the best case or the integrated configuration C producing 8000 m3/day of freshwater with NuScale could prevent releasing 0.244 million tons of CO2, about 1012 tons of SO2, and 910 tons of NOx yearly.

Fig. 13 shows the effect of hybridization degree on the exergetic efficiency in different configuration layouts. Labels show the total desalination capacity in m^3/day. As discussed earlier, the exergy loss for

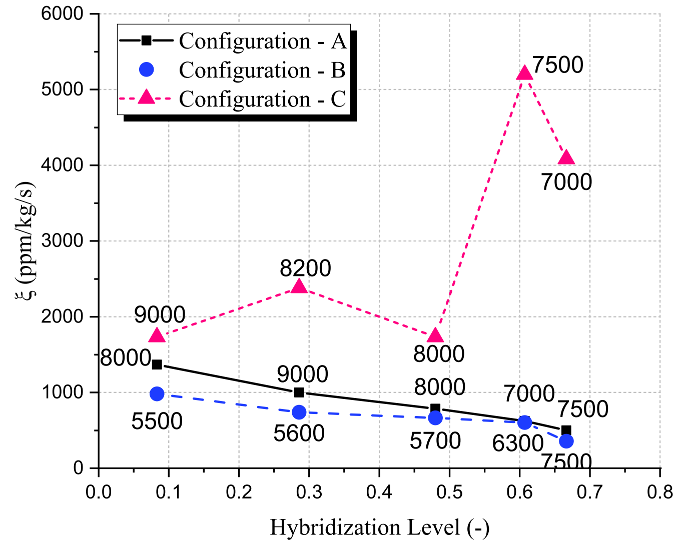


Fig. 14. The specific brine discharge salinity changes in terms of hybridization degree for different schematics.

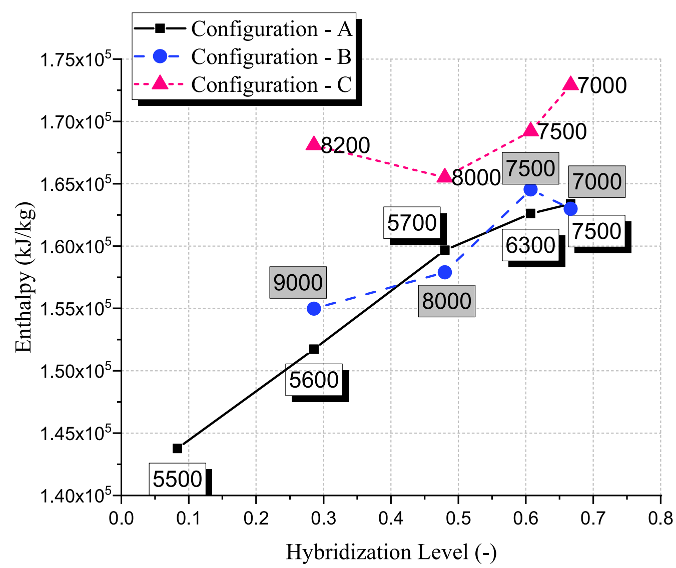


Fig. 15. The enthalpy of brine disposal changes in terms of hybridization degree for different schematics.

all configurations is almost the same. Therefore, increasing the hybridization degree or the share of thermal distillation capacity in total desalination capacity raises the amount of heat that should be extracted from the NuScale power plant, which causes the maximum available shaft work to decrease too. Therefore, it is reasonable that increasing the hybridization degree reduces the exergetic efficiency. Further, configurations B and C have higher exergetic efficiency due to slightly lower available shaft work.

Fig. 14 illustrates the effect of hybridization degree on the specific brine discharge salinity. The labels show the total desalination capacity in m3/day. It can be seen that increasing the hybridization degree generally leads to lower specific brine discharge salinity in all configurations. Further, Fig. 10 presented that the integrated configuration C has higher specific brine discharge compared to simple hybrid systems. However, a dramatic increase in specific brine discharge for the hybridization degree of 60% in configuration C could be seen. This abnormal behavior is because the MED-TVC brine discharge flow rate in the integrated configuration is three times larger than the discharge of

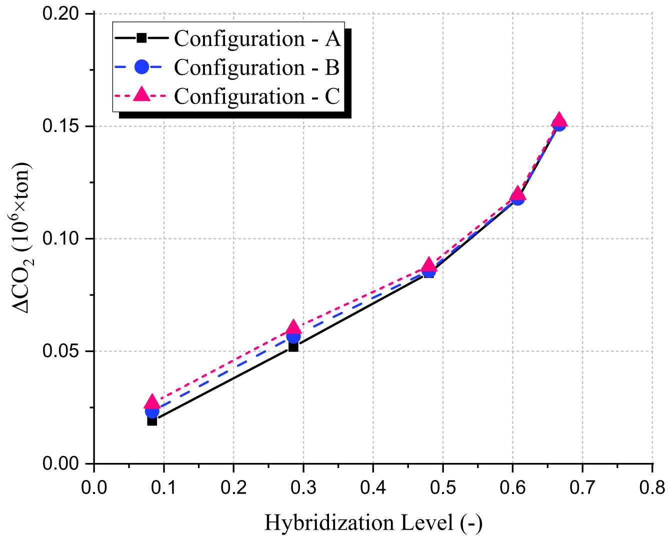


Fig. 16. The amount of CO2 is precluded from releasing into the atmosphere in different schematics.

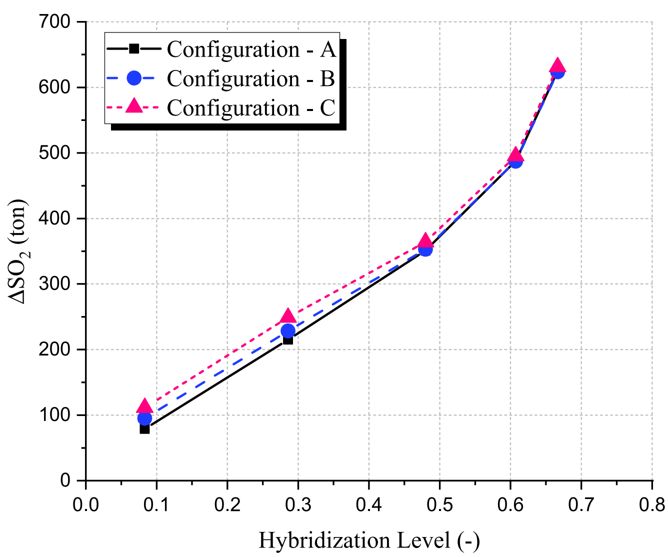


Fig. 17. The amount of SO2 is precluded from releasing into the atmosphere in different schematics.

the RO unit (Table 13), while the salinity of the RO system's discharge stream is larger two times than the MED-TVC system. This nonlinear trend in hybridization degrees above 50% leads to specific brine discharge grows sharply. In conclusion, this layout has a higher environmental impact despite the expectations and technical advantages of an integrated coupling schematic. But using measures such as WALE systems could mitigate the coastal impacts.

In Fig. 15, the enthalpy of discharge brine in terms of hybridization degree, which has a direct relationship with the discharge temperature, is demonstrated. This figure shows the total desalination capacity in m3/day. A generally increasing trend in discharge enthalpy of all configurations could be seen. This is because the discharge brine's temperature of MED-TVC and other thermal distillation processes is higher than in RO systems in which no thermodynamic cycle is involved. Further, it can be seen that the integrated hybrid system with a hybridization degree of 50% has the highest coastal effect compared with other simple schematics. However, implementing evaporating ponds could cause a decrease in the discharge brine temperature and reduce concerns about discharging hypersaline discharge with unfavorable temperatures.

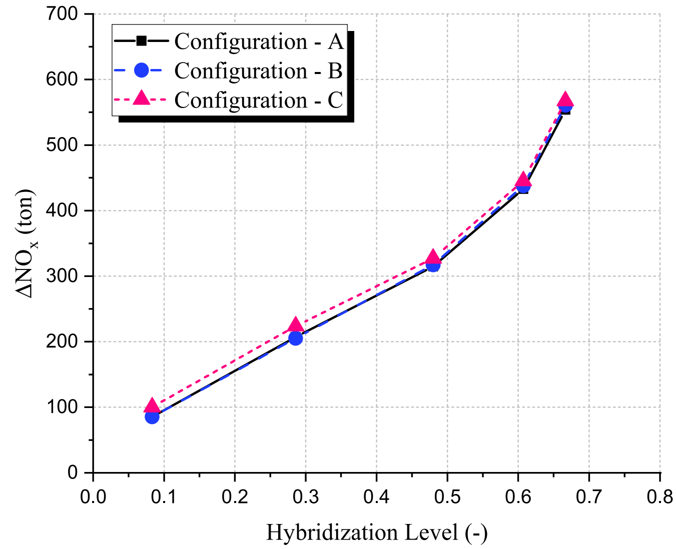


Fig. 18. The amount of NOx is precluded from releasing into the atmosphere in different schematics.

Finally, in Fig. 16, Fig. 17, and Fig. 18, the magnitude of GHG that is precluded from releasing into the atmosphere is shown, respectively. It can be seen that by increasing the hybridization degree and contribution of the thermal distillation process, the role of reactor-based plants in atmospheric impacts is increased.

Figs. 19 and 20 provide the changes in entropy to temperature of the thermodynamic cycle coupling the MED-TVC distillation unit with the NuScale power plant. As it was discussed two coupling configurations for extracting steam were considered: 1- Utilizing controlled extraction of medium-pressure steam and 2- extracting the high-pressure steam directly from the exit of the steam generator. It was discovered the location on the extraction point plays a key role and the introduced coupling configuration doesn't affect the T-S curves' trend.

Entropy changes in a thermodynamic system are described by $dS = \frac{dQ}{T} + S_{gen}$. Where, $\frac{dQ}{T}$ is due to energy transfer as heat to the system and S_{gen} is the entropy generation by irreversibility. During the reversible process, the S_{gen} term is zero. For a cyclic process, the area under the T–S curve is equal to the net heat transferred to the system during that process which is presented in Table 12.

The numbers sequence illustrated in Figs. 19 and 20 are corresponding to states demonstrated in Fig. 9. Further, points A and B present the extraction point and location of the condensate return of steam required for distillation purposes. Line 1 to 9 demonstrates the expansion of steam in a different state of a real turbine. Vertical line 9 to 10 shows the isentropic process of the condenser. The line connecting point 11 to 1 presents the state of the super-heat steam generator of the NuScale power plant. In this context, points a and b are the intermediate states of the steam generator.

Entropy changes in a thermodynamic system are described by $dS = \frac{dQ}{T} + S_{gen}$. Where, $\frac{dQ}{T}$ is due to energy transfer as heat to the system and S_{gen} is the entropy generation by irreversibility. During the reversible process, the S_{gen} term is zero. For a cyclic process, the area under the T–S curve is equal to the net heat transferred to the system, which is presented in Table 12.

The numbers sequence illustrated in Figs. 19 and 20 correspond to states demonstrated in Fig. 9. Further, points A and B present the extraction point and location of the condensate return of steam required for distillation. Line 1 to 9 demonstrates the expansion of steam in a different state of an actual turbine. Vertical line 9 to 10 shows the isentropic process of the condenser. The line connects points 11 to 1 and presents the state of the superheating steam generator of the NuScale

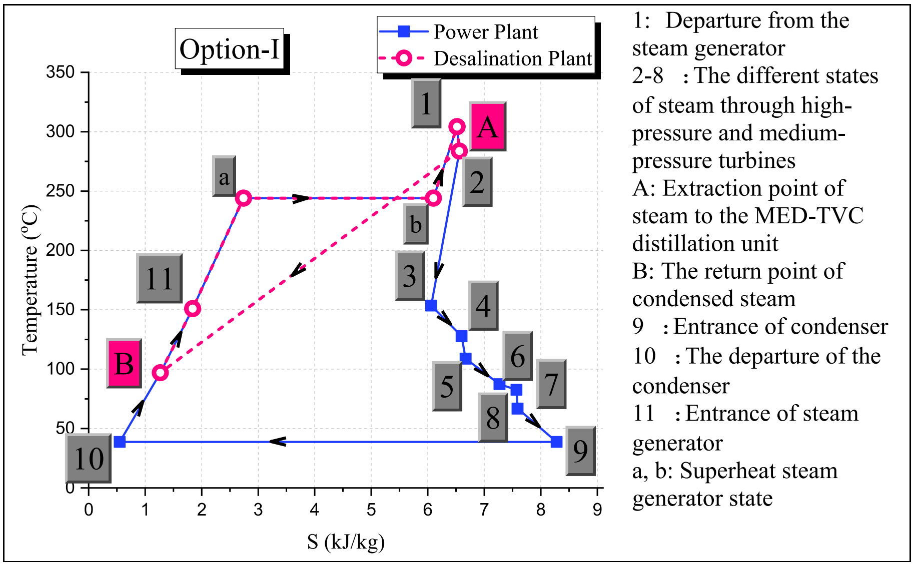


Fig. 19. The T-S diagram of thermally coupled MED-TVC unit with NuScale power plant through Option-I scheme.

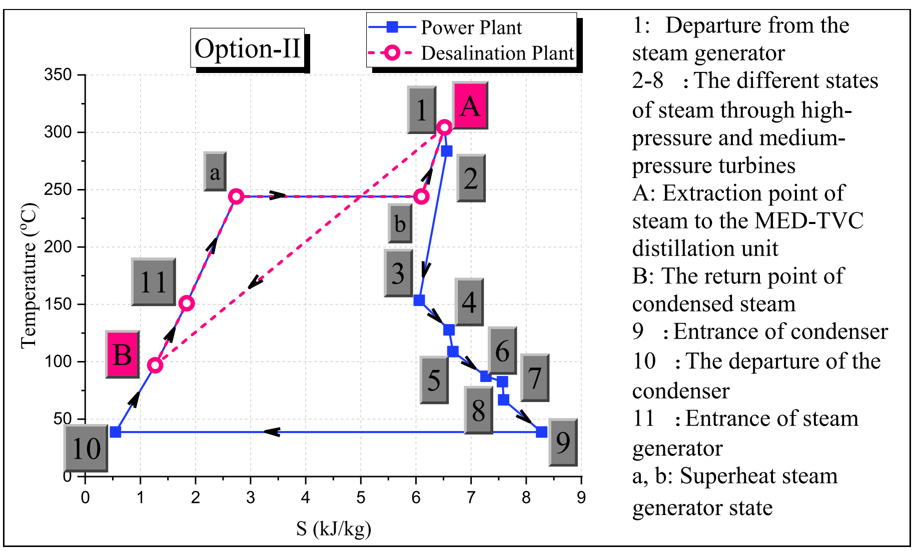


Fig. 20. The T-S diagram of thermally coupled MED-TVC unit with NuScale power plant through Option-II scheme.

power plant. In this context, points of a and b are the intermediate state of the steam generator.

9. Conclusions

The potential to deliver extensive amounts of cheap, stable, and environmentally friendly energy could be the primary motive in justifying the public and experts' attention to different technical, economic, and social aspects of reactor-powered desalination. The existing RD concept is derived from the successful experience of integrating the liquid metal-cooled fast breeder reactor (LMFBR) BN-350 in Aktau, Kazakhstan, with a MED process plant in 1973, which demonstrated the technical feasibility and proved the reliability and compliance of the safety cogeneration with reactors as well as competence of conventional fossil fuel energy sources (IAEA, 2015). Reviewing the literature shows a rapid rise in the thermo-economic assessment of large-scale reactor-powered desalination plants. Meanwhile, despite all the efforts in large-scale reactor power reactors, SMRs are a promising alternative for powering desalination plants. Moreover, there is a lack of study on the environmental aspects of RD with SMRs. This study critically assesses the environmental impacts of three zero liquid discharge hybrid desalination configurations coupled with one NuScale power plant module. Five performance parameters, including exergetic efficiency, Power-to-Water ratio, specific discharge salinity, seawater-to-brine ratio, discharge enthalpy, and net greenhouse gas emissions, were precluded with all the necessary formulas presented to analyze the different techno-environmental aspects of hybrid desalination layouts. The high salinity of effluent discharge is desalination facilities' most serious environmental concern. The high salinity of the brine combined with unfavorable temperature and pH values caused by preheating and chemical pre-treatment of the incoming seawater can produce undesirable marine impacts. Hence, the authors have paid more attention to the magnitude and quality of the desalination waste discharge.

While the environmental and sustainable benefits of seawater desalination are evident for greener desalination, the economic feasibility of layouts will always be one of the deciding factors. Therefore, more research on financial aspects such as the costs of pre-treatment and after-treatment and measures is still necessary before designing an SMR zero liquid discharge hybrid desalination plant. Based on the promising findings presented in this paper, work on the economic issues is continuing. This research was concerned with the reactor-based desalination approach; however, the implemented methodology can also be applied to other desalination plants, such as fossil-fueled and thermal solar power plants.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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